

Annual Project Summary

DEEP BOREHOLE TENSOR STRAIN MONITORING, NORTHERN CALIFORNIA

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seismology, geodesy, borehole geophysics

Project Objectives and Approach

This project provides field observations contributing to an understanding of fault processes associated with earthquakes along the San Andreas and Hayward faults. Continuous high precision and high resolution borehole tensor strain data provide a high value complement to GPS based geodetic studies and seismic characterisation of faults.

The project continues a program of maintenance and analysis of deep borehole tensor strain instrumentation. One system was installed at San Juan Bautista in late 1983, three in the Parkfield area during December of 1986, and two near the Hayward Fault in the San Francisco Bay region in 1992. Each instrument consists of a three component plane strain module operating at a strain sensitivity of 10^{-10} and support data logging systems. Systems provide unique continuous tensor strain data of high quality at 30 minute intervals for transmission via satellite to permanent archive. These data form a critical complement to GPS and geodetic studies (see Figure 1) in assessing strain rates and consequent earthquake risk, as well as investigating fault processes associated with earthquake preparation and post-seismic relaxation.

Archived data are available from <http://www.cat.csiro.au/dem/msg/straincal/straincal.html>. Automatically processed data are also made available in near real time in the USGS Menlo Park computer system (*thecove:/home/mick/QUICKCHECK*) to permit real time monitoring for short term strain phenomena.

The **immediate objectives** of the project are

- Maintenance of uphole system integrity at 5 Northern Californian sites, with repair or production of replacement uphole electronics as necessary.
- Manual preparation of raw instrument data for permanent archive.
- Analysis of continuous unique low frequency shear strain data (30 minute samples) and modelling studies based on the constraints of these data
- Regular reporting and real time alert response as part of the Parkfield Prediction experiment.
- Archive of processed data for access by the earthquake studies community, and provision of near-real time automatically processed data for inclusion in publicly accessible web pages linked to the USGS web datasets.

The project is carried out in parallel with maintenance of two further sites (Pinon Flat and San Gabriel mountains) in Southern California.

Investigations & Results

1. Data handling

During the year to October 2003, models of the recovery of the disturbance of the regional strain field caused by the drilling of the borehole have been completely reviewed. These effects, which are necessarily superimposed on the tectonic observations, are removed from the data for convenience in interpretation. New models exploiting the quite long lengths of GTSM data streams available (**Table 1** below) are expected to be better than those previously used, which were calculated early in the station lifetimes from much shorter lengths of data. Depending on the particular site, the least squared models remove one or two exponential recovery processes, static offset and long term drift.

Stn	Gge	Fit....	Days Fitted
Pft	 Record length = 6895 days	
	1	$y1 = 5857.48 + (8501.62 \cdot \exp(-0.0124450 \cdot t/80)) + (-2.9928358 \cdot t/80)$	1-300,3600- 5200
	2	$y2 = 6186.50 + (12468.30 \cdot \exp(-0.0044795 \cdot t/80)) + (-2.8388492 \cdot t/80)$	1-300,3600- 5200
	3	$y3 = 1512.26 + (19224.64 \cdot \exp(-0.0022316 \cdot t/80)) + (-1.1909949 \cdot t/80)$	1-300,3600- 5200
Sjt	 Record length = 6879	
	1	$y1 = 31397.93 + (23320.64 \cdot \exp(-0.0018199 \cdot t/80)) + (-4.1875848 \cdot t/80)$	300-2000,6600-6600
	2	$y2 = 35914.76 + (-9691.66 \cdot \exp(-0.0019959 \cdot t/80)) + (3.2801976 \cdot t/80)$	200-2000,6800-6800
	3	$y3 = 8944.70 + (23475.91 \cdot \exp(-0.0004877 \cdot t/80)) + (0.0743084 \cdot t/80)$	2500-6000,6800-6800
Dlt	 Record length = 5763 days	
	1	$y1 = -27777.5 + (43734.70 \cdot \exp(-0.0008255 \cdot t/80)) + (-4.4761785 \cdot t/80);$	300-5763
	2	$y2 = 53127.09 + (-88175.93 \cdot \exp(-0.0010795 \cdot t/80)) + (14.9234978 \cdot t/80)$	300-5763
	3	$y3 = -72113.74 + (125477.14 \cdot \exp(-0.0007602 \cdot t/80)) + (-19.1466265 \cdot t/80)$	300-5763
Flt			
	1	$y1 = 3073.55 + (-4979.9 \cdot \exp(-0.0009571 \cdot t/48)) + (-0.3932092 \cdot t/48)$	740-4000
	2	$y2 = -4477.07 + (10909.93 \cdot \exp(-0.0013719 \cdot t/48)) + (-1.9986600 \cdot t/48)$	740-4000
	3	$y3 = -1139.36 + (2439.43 \cdot \exp(-0.0008535 \cdot t/48)) + (-0.3951845 \cdot t/48)$	740-4000
Edt	 Record length = 5603 days	
	1	$y1 = -17978.9 + (42286.23 \cdot \exp(-0.0016692 \cdot t/48)) + (-4.4714247 \cdot t/48)$	500-2000,3000-4000
	2	$y2 = -5665.15 + (15083.79 \cdot \exp(-0.0015208 \cdot t/48)) + (-2.3186453 \cdot t/48)$	500-2000,3000-4000
	3	$y3 = -9864.91 + (24585.1 \cdot \exp(-0.0019508 \cdot t/48)) + (-0.0890765 \cdot t/48)$	500-2000,3000-4000
Gat	 Record length = 2159	
	1	$y1 = 19003.09 + (-22953.56 \cdot \exp(t/48 \cdot (-0.0029998))) + 4.4996150 \cdot t/48;$	40-700,1000-2000
	2	$y2 = -22742.56 + (13475.41 \cdot \exp(t/48 \cdot (-0.0021997))) + -7.1186465 \cdot t/48;$	40-700,1000-2000
	3	$y3 = -33254.52 + (19509.29 \cdot \exp(t/48 \cdot (-0.0033239))) + -7.0251764 \cdot t/48;$	40-700,1000-2000
	4	$y4 = 26579.19 + (-23694.95 \cdot \exp(t/48 \cdot (-0.0028800))) + 3.6708072 \cdot t/48;$	40-700,1000-2000
Cht	 Record length = 3585 days	
	2	$y2 = -27306.87 + (14360.03 \cdot \exp(0.0101519 \cdot t/48)) + (-1.6901718 \cdot t/48)$	1-1150, 1150-3500
	3	$y3 = 35326.82 + (-38239.52 \cdot \exp(-0.0067137 \cdot t/48)) + (0.6107154 \cdot t/48)$	50-1150, 1150-3500
	4	$y4 = 81846.54 + (-96593.93 \cdot \exp(-0.0058567 \cdot t/48)) + (0.0756670 \cdot t/48)$	50-1150, 1150-3500
Clit	 Record length = 2351	
	1	$y1 = -14971.39 + (5680.42 \cdot \exp(t/48 \cdot (-0.0422210))) + (8945.59 \cdot \exp(t/48 \cdot (-0.0025802))) + 0.1393232 \cdot t/48$	1-100, 100-2000
	2	$y2 = -8090.69 + (5012.65 \cdot \exp(t/48 \cdot (-0.0490979))) + (2989.44 \cdot \exp(t/48 \cdot (-0.0042232))) + 1.1925344 \cdot t/48;$	1-1000, 100-2000
	3	$y3 = -16841.74 + (7901.41 \cdot \exp(t/48 \cdot (-0.0478592))) + (8810.76 \cdot \exp(t/48 \cdot (-0.0052106))) + 0.0014103 \cdot t/48$	1-100, 100-2000
	4	$y4 = -23285.65 + (9759.57 \cdot \exp(t/48 \cdot (-0.0358192))) + (12831.58 \cdot \exp(t/48 \cdot (-0.0034245))) - 1.2898408 \cdot t/48$	1-100, 100-2000

Table 1: Borehole recovery models

2. Parkfield

2.1 Parkfield 1997 Regional Event

In 1999, this project first identified a regional anomaly in the Parkfield area beginning in 1997/98. The anomaly appears to be continuing over the whole Parkfield region. The GTSM data is shown in **figure 1**. A previous anomaly beginning in 1993 and first reported in 1995 was subsequently confirmed by independent observations (Nadeau and McEvilly, 1999; Langbein et al., 1999, and Gau et al., 2000).

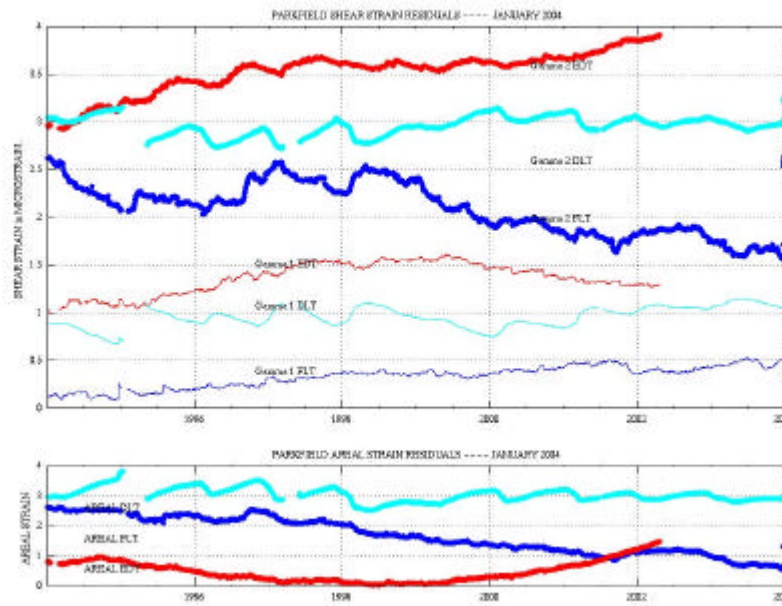
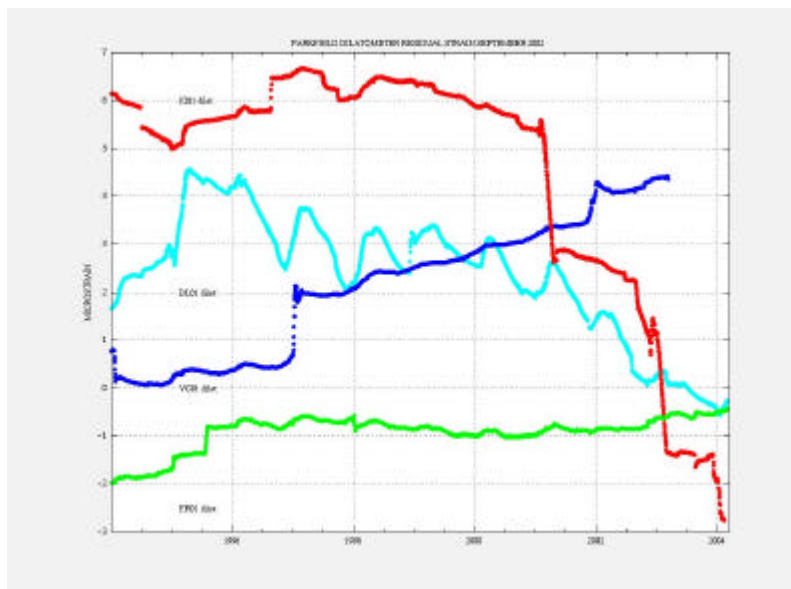


Figure 1: GTS data for Eades, Frolich and Donna Lee sites at Parkfield showing the long term dominantly shear strain rate anomaly beginning in late 1997.



Recently, the archived dilatometer data collected by USGS has been made available. These data have been subjected to the same type of processing as the tensor data, (ie removal by least squares fitting of borehole recovery effects). We have confirmed that the change in rate beginning in 1997 is also observed in some of the dilatometers. The data from four of the dilatometers associated with our instruments are shown in **figure 2**.

Figure 2. Dilatometer data for sites Joachin Canyon, DonaLee, Vinyard Canyon and Frohlich from the USGS archive. These data also indicate changes of strain rate beginning in 1997/98.

2.2 August 20, 2003, Parkfield Strain event in response to EQ swarm.

A series of small earthquakes occurred near Parkfield in mid August, 2003, and were accompanied by strain events on Frohlich. Associated creep events on the USGS network followed later.

Date	Location	Depth	Magnitude	Distance
2003/08/20 18:46	35.9245 -120.4702	5.45	1.09	2.09
2003/08/20 21:00	35.9255 -120.4717	4.52	0.09	2.08
2003/08/22 17:28	35.9707 -120.5187	11.63	2.14	7.29
2003/08/28 00:11	35.9230 -120.4703	6.26	3.05	1.96

Some rain (0.01 inches) fell on 21/8/2003 at 9:00 and may have influenced the creep event. The association of the strain and creep events (both probably triggered by the earthquakes shown on the plot) are shown below. As is usual, the strain events preceded the creep events.

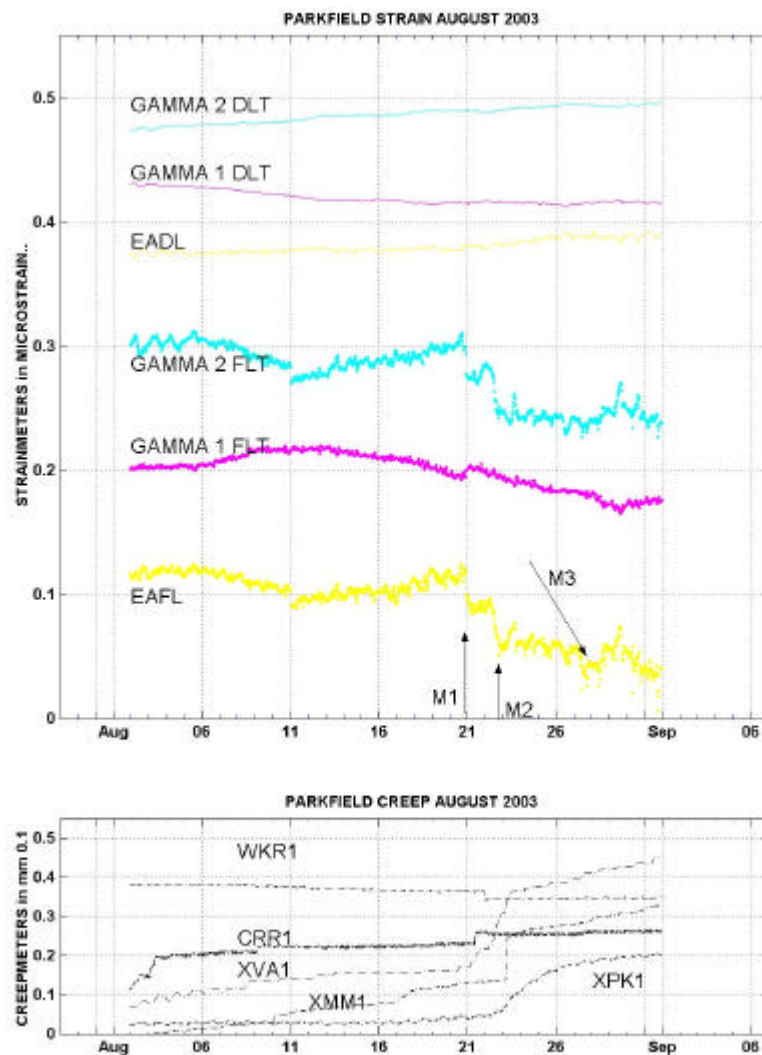


Figure 3. Response at DonnaLee and Frolich near the August 20 event.

3. San Juan Bautista

3.1 Slow Earthquake/Transient slow event at San Juan Bautista July, 2003

We continue to observe coseismic offsets associated with earthquakes in the vicinity of the strainmeter site at San Juan Bautista. **Figure 4** illustrates a recent (2003/07/12 19:45:47.27) offset which began with the M3.2, 2km deep, approximately 3km west of the SJT site. (NCSN 51129852).

The event is dominantly shear, and the associated coseismic strain steps are
 $\text{easj} = +19.4\text{n}\epsilon$, $\text{gam1sj} = -71.7\text{n}\epsilon$, and $\text{gam2sj} = -71.6\text{n}\epsilon$.

The slow (aseismic) transient which followed this event resulted in a further $-410\text{ n}\epsilon$ over 17 days in gamma 1, and a further $-310\text{ n}\epsilon$ over 10 days in gamma 2.

This event is seen only in the shears, the areal registering only a small co-seismic step. The creep meters of the region do not measure any change, until the Cwn signal on July 29.

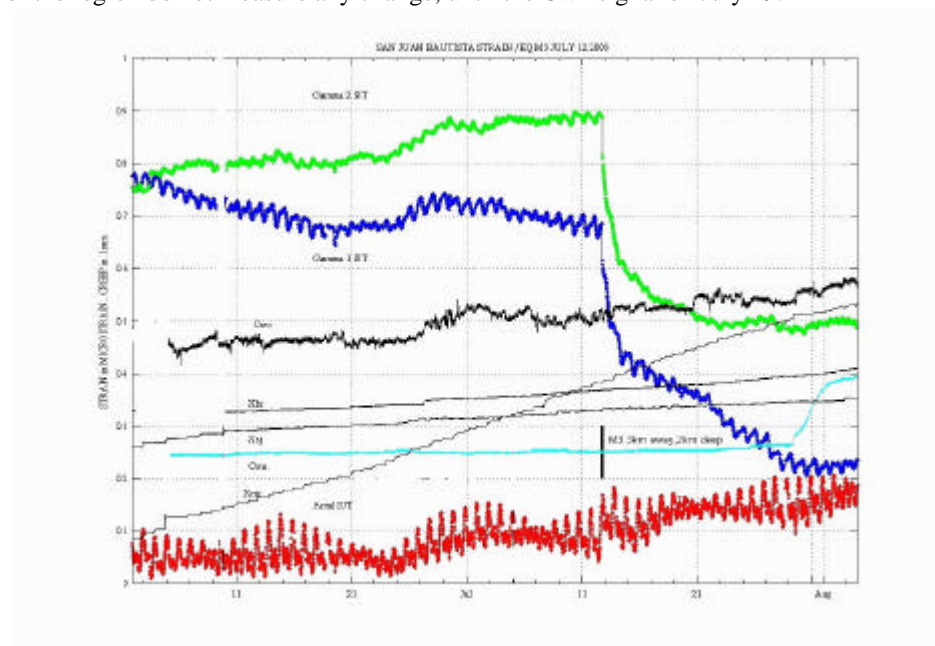


Figure 4 Coseismic and aseismic transient caused by July 13, 2003, M3.21 at SJT.

The size of the transient is similar to one previously observed at SJT in August 1998. **Figure 5**, below gives a comparison of the 2 events, the both of which are estimated to be approximately M4.9.

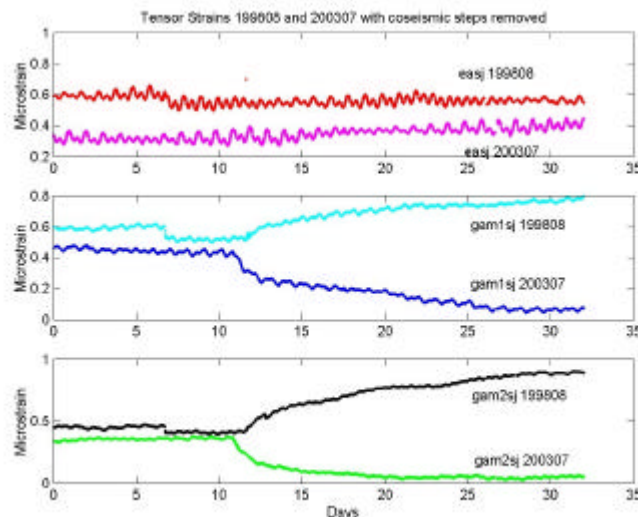


Figure 5. Comparison of M4.9 slow events at SJT in August 1998 and July 2003. The time constants are remarkably similar for the two events, and neither event shows significant areal strain. Note the earthquake step has been removed from all data.

3.2 Suite of Strain –Creep events at San Juan Bautista

An extensive suite of creep strain events at San Juan Bautista has been reported previously in various reports, and AGU presentations, and papers (*Gladwin et al, 1994*). These events are related to repeated failure on a small region of the fault below the SJT and Xsj sites. **Table 2** below details these events to date.

easj ne	gam1sj ne	gam2sj ne	Xsj Mm	year	day
-60	-80	-35	1.1	1985	j046
-70	-95	-45	3.7	1986	j106
-142	-173	-88	6	1987	j231
-30	-35	-35	0	1988	j086
-80	-100	-40	1.7	1988	j236
-94	-115	-59	4	1989	j290
-60	-77	-38	0.5	1989	j356
-53	-69	-41	0.6	1990	j027
-75	-90	-55	1.9	1990	j097
-90	-100	-50	3.9	1990	j160
-91	-120	-52	3.2	1990	j242
-70	-50	-45	2.1	1990	j324
-80	-95	-50	3.6	1991	j067
-90	-120	-50	5	1991	j218
-80	-90	-50	0.3	1991	j361
-90	-110	-45	5.3	1992	j159
-70	-135	-59	3.3	1992	j349
-190	-85	-54	5.7	1993	j166
-100	-87.5	-52	3.25	1993	j335
-68	-100	-49	5.8	1994	j180
-111	-136	-69	4.7	1995	j049
-60	-120	-60	4.55	1995	j204
-55	-70	-49	4.2	1996	j139
-45	-65	-60	0	1996	j269
-70	-74.5	-41	3.8	1997	j032
-45	-80	-50	4.03	1997	j258
-50	-70	-45	4.5	1998	j219
-95	-130	-35	4	1998	j298
-50	-90	-65	6	1999	j181
-85	-105	-55	4	1999	j352
-70	-120	-58	X	2000	j178
-70	-75	-52	0.11	2000	j361
-66	-91	-36	3.2	2001	j086
-80	-105	-55	6.2	2001	j255
-70	-103	-43	5	2002	j178
-85	-95	-40	5.2	2002	j325
-60	-66	-63	0.65	2003	j147
-70	-130	-65	3.8	2003	j357
-75	-90	-55	3.8	2004	j081

Table 2: Suite of strain creep events at San Juan Bautista from 1985 to 2004 with the advisory that when either instrument was off line, then it is not recorded or is reported as 'x'. Following the Loma Prieta event in 1989, the rate of events has decayed from a peak of five events per year in 1990 to approximately two per year which appears to be the background rate for this area.

3.3 Strain Creep prior San Simeon Earthquake M 6.5 of Dec 22 ,2003

Comparison *(Figure 6)* of the 4 strain-creep events prior to the San Simeon Earthquake reveals anomalous behaviour. For the strain, the maximum shear is plotted. The creep at the surface of the 03j147 event (several months before the San Simeon event) is totally anomalous in the series where most of the events are completed after two days. For the 03j147 event there is a creep strain rate change which has continued through to the slow earthquake of July 13 as shown in *Figure 7*.

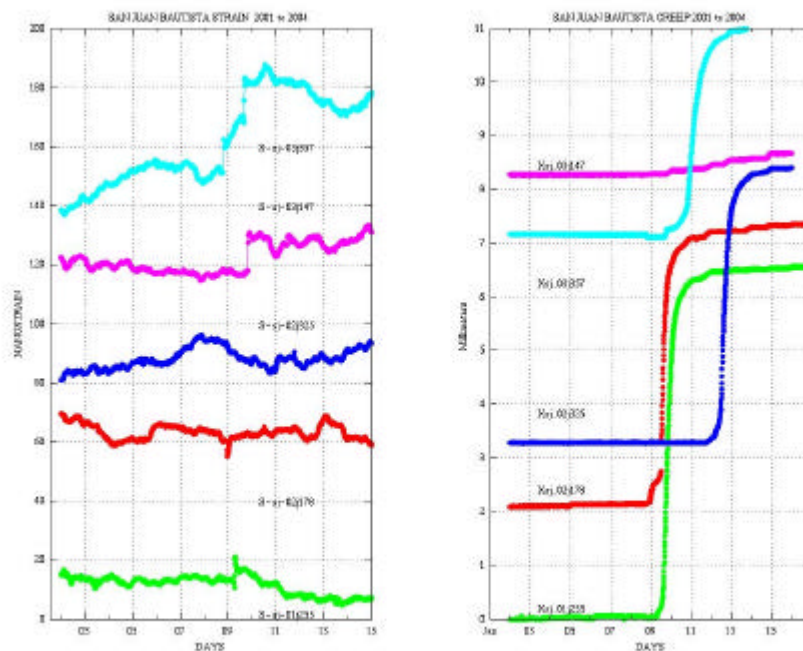
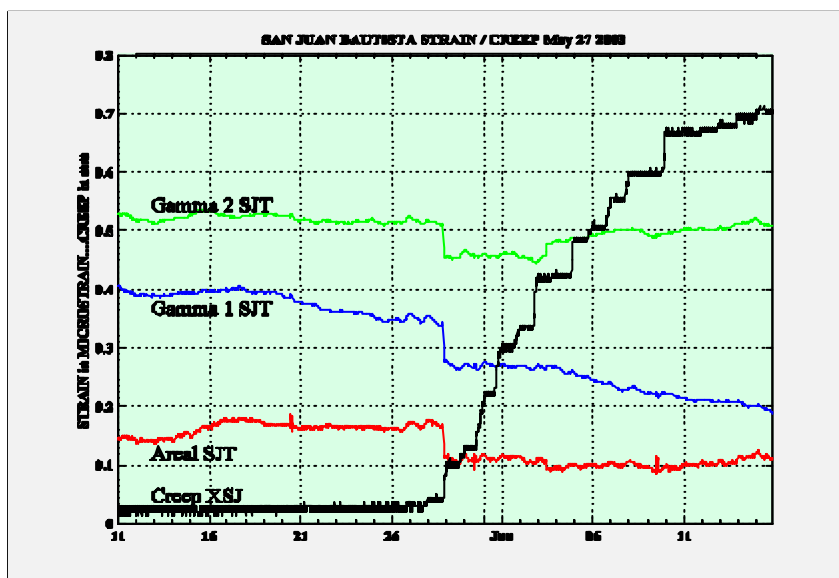


Figure 6 Comparison of strain creep events prior to the San Simeon Earthquake of Dec22, 2003

3.4 Continued Creep strain events at SJT.

A further creep strain event (no 37) occurred in the San Juan area on May 27, 2003. The event shown



(Figure 7) is atypical in that strain step sizes do not fit the previously recorded profile, and in that the accompanying creep signal (plotted in tenths of a mm) is very slow, 0.65mm over 14 days. The slip activity, for a total of 1.3mm, continued for 3 months more into September, right through the slow transient of July 13 described above in

Figure 6.

Figure 7: Closeup of May 27, 2003 (03j147) anomalous creep at XSJ.

Another non associated strain event at San Juan Bautista occurred in June, 2002, and was reported previously. The event showed dominantly on the gamma one component, and was not accompanied by any creep on the nearby creep meters, confirming that the source region was different from those in our current creep strain catalog. The event was followed ten days later by a sequence of creep events over the region. The data is shown in **Figure 8**. Delays this long are unusual for the region, though they are common in the Parkfield area.

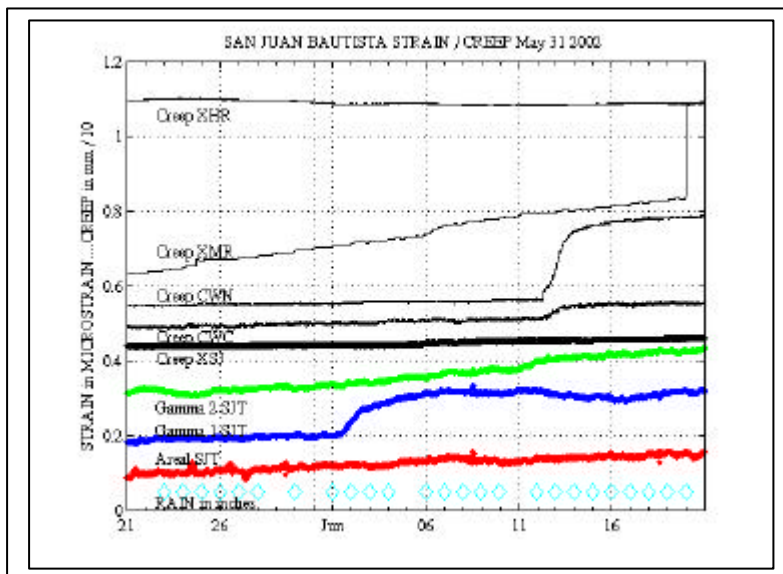


Figure 8. Atypical Creep strain association for the San Juan Bautista area. The event occurred dominantly on gamma 1, and the only creep response was delayed many days

Both above events fall outside the ‘normal’ profile of strain/creep events catalogued by this program over 20 years.

4. Regional East Bay Signal

We have reported previously the continuing apparent anomalous strain and tilt signal in the East San Francisco Bay area. **Figure 10** details the CHT tensor strain and tilt data. Gamma1 and tilt N-S are continuing to show the previously identified trend. **Figure 9** includes the dilatometer data (GA01 and RR01) which also seem to confirm some regional anomaly is being observed.

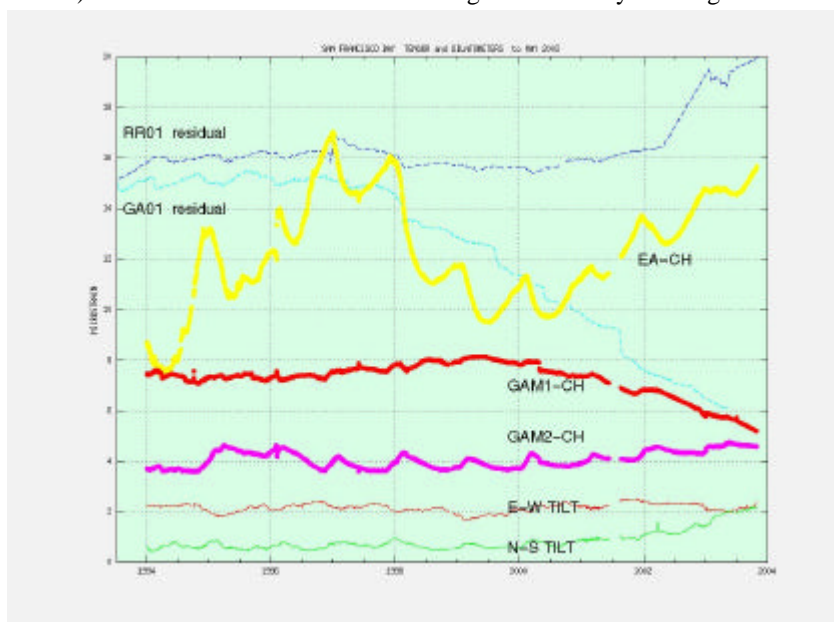


Figure 9 .Comparison of East Bay dilatometers with Chabot GTS. For compatibility, exponential detrends

have been removed from the dilatometer data to produce residuals in the manner used for the GTSM data. Dilatometer data have been inverted to the compression negative convention.

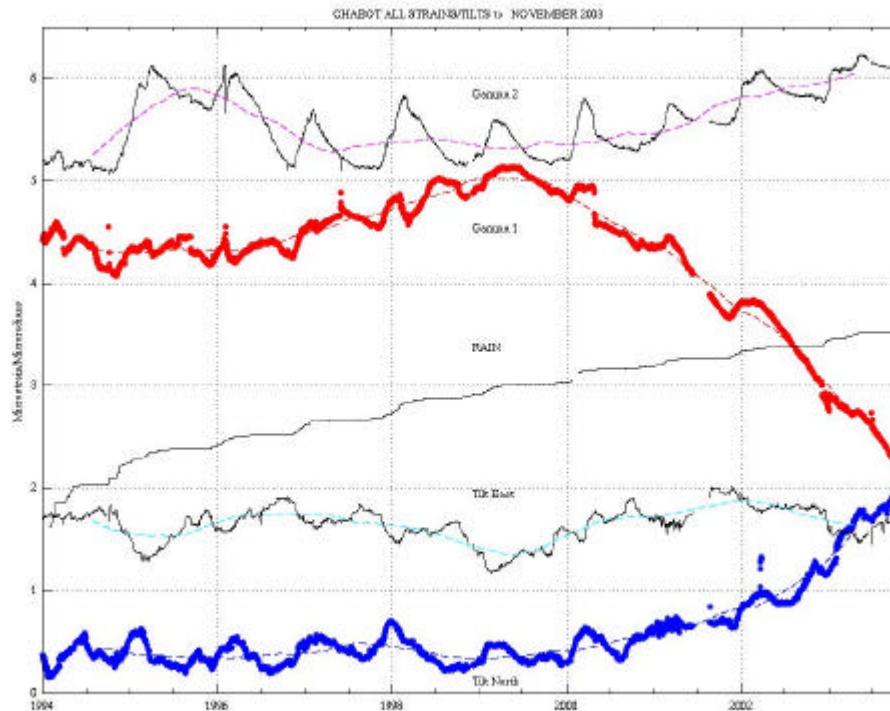


Figure 10: Chabot GTS shears and tilt data from 1994

Data Availability

Archived strain data from the Californian sites are stored in both raw component form, and as processed areal and shear strains. A regularly updated archive of data has been maintained in the USGS Menlo Park computer system since 1988. This data is stored in binary files with appended header information (USGS “*bottle*” format).

Home page for access to data plots from all borehole tensor strain instruments is <http://www.cat.csiro.au/dem/msg/straincal/straincal.html>. *This page also includes facilities for download of raw or processed data from our main archive.*

Automatically processed near-realtime data is available in *thecove:/home/mick/QUICKCHECK* for users with access to USGS plotting software “*xqp*”, and via the USGS crustal deformation web pages in graphical form.

Scientists requiring other access to the archived data should contact Dr. M.T. Gladwin (+617 3212 4562).

Publications

Recent Publications

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Non-Technical Summary

DEEP BOREHOLE TENSOR STRAIN MONITORING, NORTHERN CALIFORNIA

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seismology, geodesy, borehole geophysics

This project provides field observations of horizontal strain changes over timescales from minutes to years, critical to an understanding of fault processes associated with earthquakes along the San Andreas and Hayward fault systems. It continues a program of maintenance and analysis of deep borehole tensor strain instrumentation initiated at San Juan Bautista and Pinon Flat Observatory in late 1983. Three further instruments were deployed near Parkfield in central California in 1986, and two instruments were deployed near the Hayward fault in 1992. A series of episodic strain events associated with surface creep events have been observed at Parkfield, similar to those previously reported at San Juan Bautista. A regional strain anomaly at Parkfield first reported in 1994 has been confirmed by other instrument types, and a second event beginning in late 1997 is continuing. The occurrence of episodic events is directly related to longer term changes in strain rate at these sites, and suggests processes for stress transfer from medium to shallow depths of the fault. Persistence of an apparent strain tilt anomaly at the East San Francisco Bay site is confirmed from other instrumentation, and may relate to the loading of the Lake Chabot during the period. This project runs in parallel with a maintenance project covering two further instruments in Southern California.